US009203234B2

US 9,203,234 B2

(12) **United States Patent**
Pence et al.

(10) **Patent No.:** **US 9,203,234 B2**
(45) **Date of Patent:** **Dec. 1, 2015**

(54) **FAULT DETECTION SYSTEM AND METHOD FOR A GENERATOR**

(71) Applicant: **Deere & Company**, Moline, IL (US)

(72) Inventors: **Jacob Pence**, Dubuque, IA (US); **Eric Vilar**, Dubuque, IA (US)

(73) Assignee: **DEERE & COMPANY**, Moline, IL (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 252 days.

(21) Appl. No.: **13/751,216**

(22) Filed: **Jan. 28, 2013**

(65) **Prior Publication Data**

US 2014/0211344 A1   Jul. 31, 2014

(51) **Int. Cl.**
H02P 1/00   (2006.01)
H02H 7/125   (2006.01)
H02H 7/06   (2006.01)

(52) **U.S. Cl.**
CPC *H02H 7/1252* (2013.01); *H02H 7/06* (2013.01); *Y02T 10/6286* (2013.01); *Y02T 10/7077* (2013.01)

(58) **Field of Classification Search**
CPC . Y02T 10/7005; Y02T 10/7077; B60W 10/08

USPC 318/139, 727, 140
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,229,687	A	*	10/1980	Newman	320/112
4,542,462	A	*	9/1985	Morishita et al.	701/1
5,617,011	A	*	4/1997	Hammer et al.	322/28
6,098,735	A	*	8/2000	Sadarangani et al.	180/65.24
7,459,914	B2	*	12/2008	Lindsey et al.	324/525
7,652,858	B2	*	1/2010	Tang et al.	361/33
8,108,160	B2	*	1/2012	Liu et al.	702/63
2012/0277942	A1		11/2012	Vilar et al.	

FOREIGN PATENT DOCUMENTS

JP	2003087996 A	3/2003
JP	2006254692 A	9/2006
WO	WO2010073552 A1	7/2010

* cited by examiner

Primary Examiner — Rina Duda
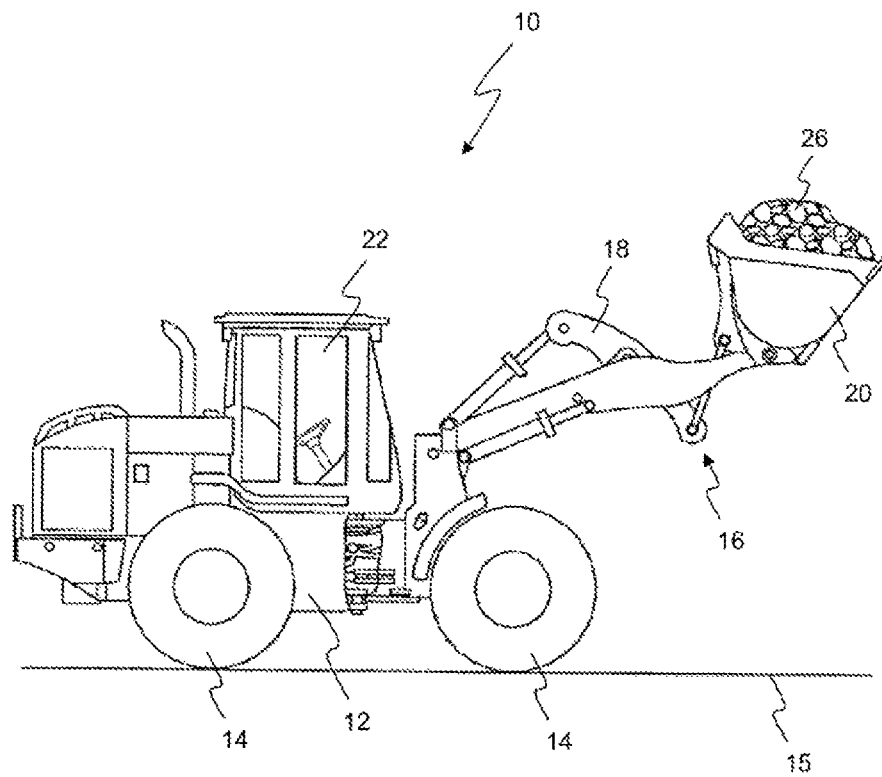
(57)   **ABSTRACT**

An electric vehicle is provided having an electric generator and a motor. Generated electrical energy may be routed to a DC bus of an inverter system. The inverter system may be configured to provide the electrical energy to the motor. A controller may detect a fault based on the voltage level of the DC bus.

17 Claims, 4 Drawing Sheets

FIG. 1

FIG. 2

FIG. 3

DETECT FAULT $\quad$ 102

↓

OPERATE ENGINE AT IDLE SPEED $\quad$ 104

↓

DISABLE GENERATOR CONTROL $\quad$ 106

↓

BLEED DOWN DC BUS VOLTAGE $\quad$ 108

↓

GENERATOR LOADS DISABLED? $\quad$ 110

NO

YES

↓

MONITOR DC BUS VOLTAGE AND GENERATOR SPEED $\quad$ 112

↓

DC BUS VOLTAGE > THRESHOLD? $\quad$ 114

NO → DECREMENT FAULT COUNTER $\quad$ 116

YES

↓

INCREMENT FAULT COUNTER $\quad$ 118

FAULT COUNT > THRESHOLD? $\quad$ 120

↓

PHASE TO PHASE FAULT DETECTED $\quad$ 124

↓

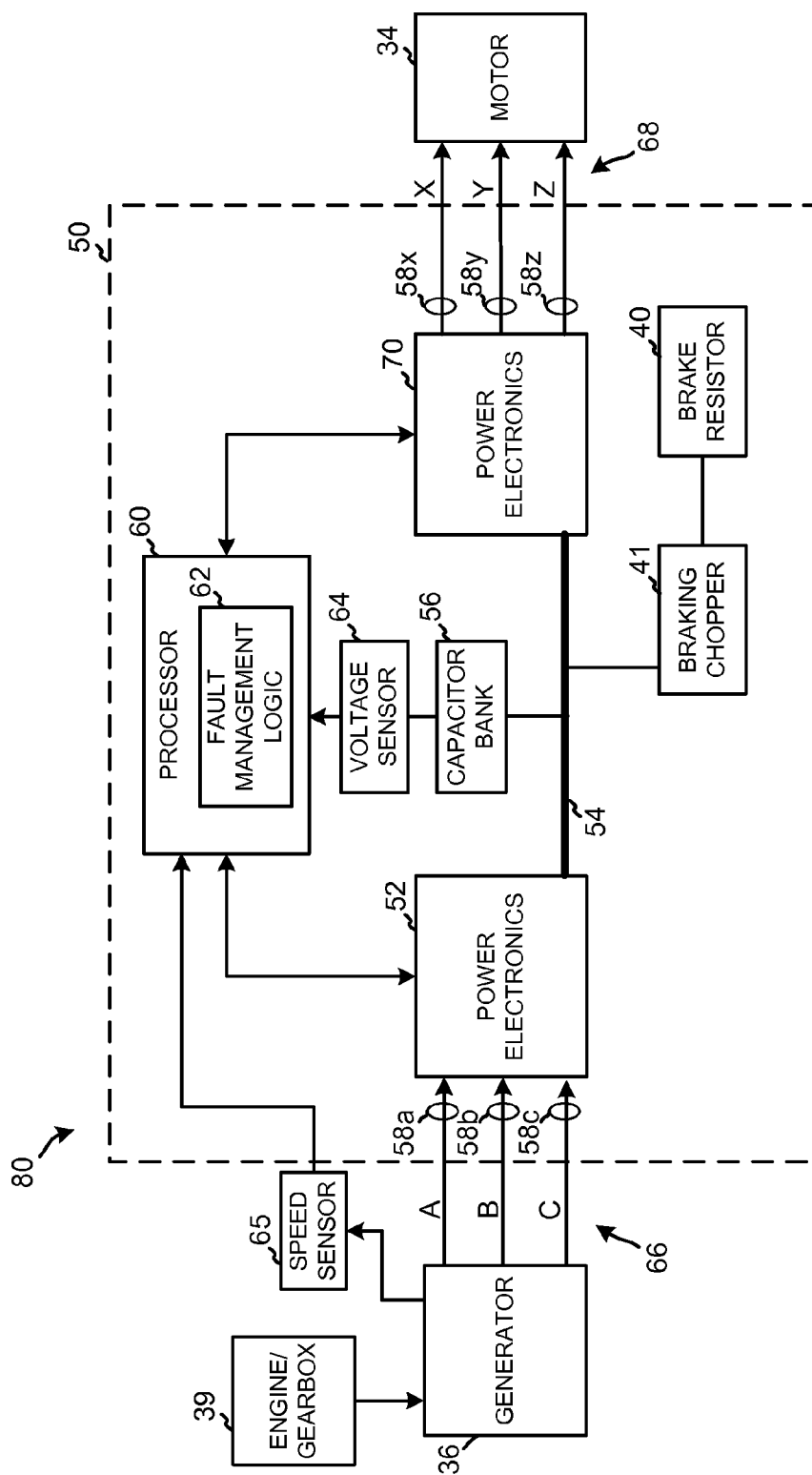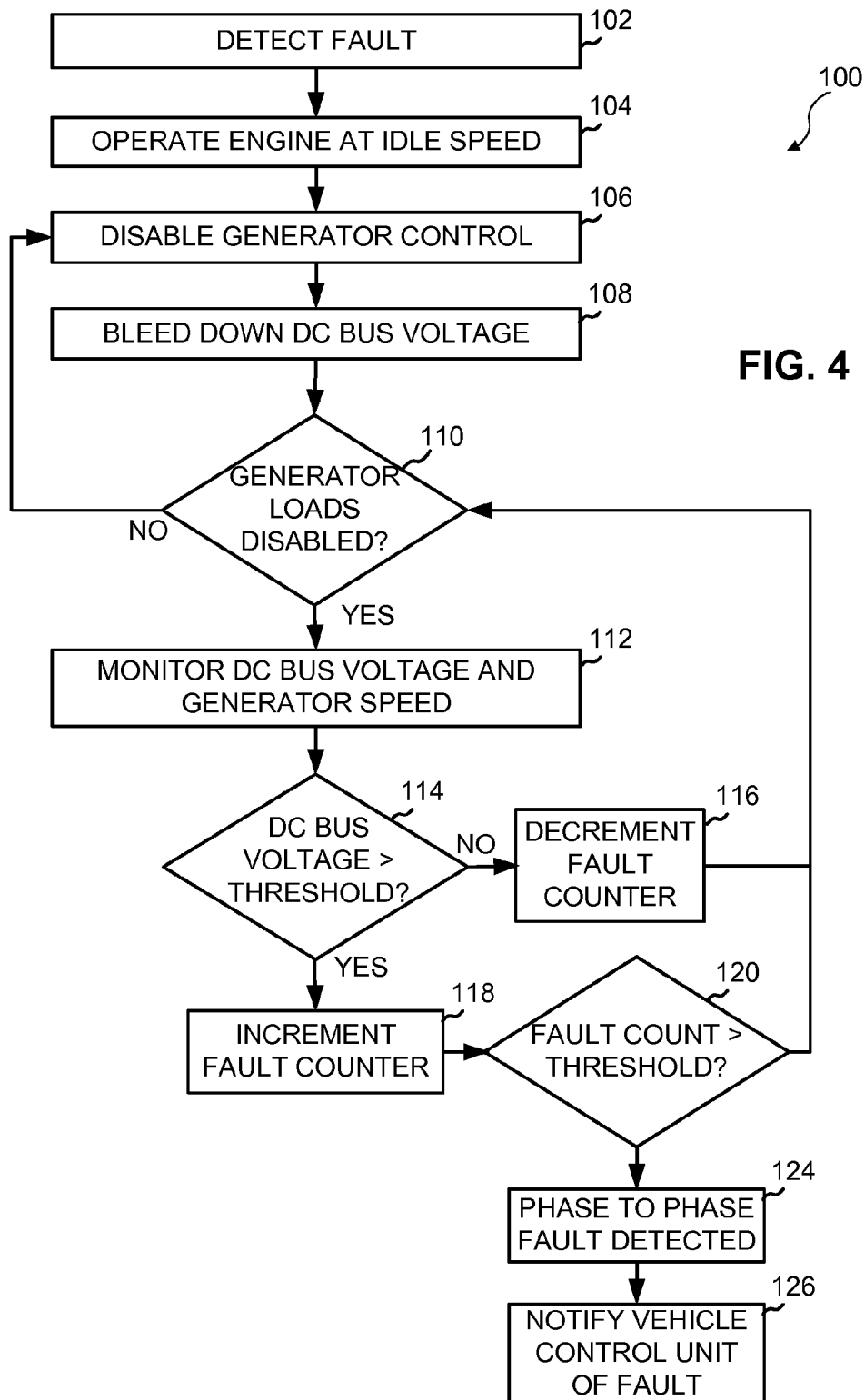NOTIFY VEHICLE CONTROL UNIT OF FAULT $\quad$ 126

FIG. 4

100
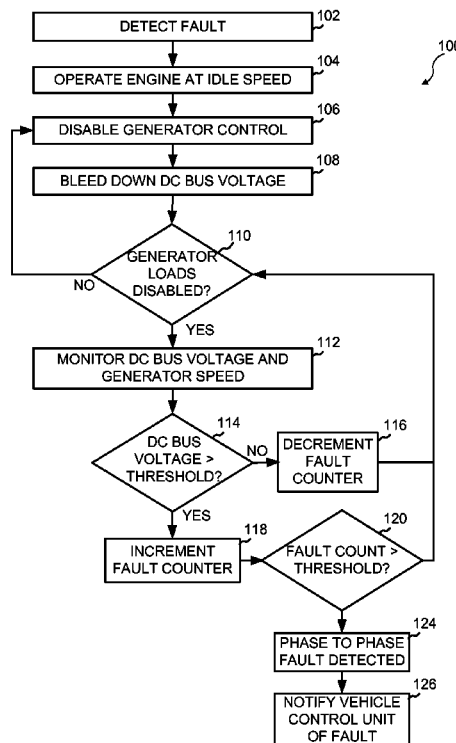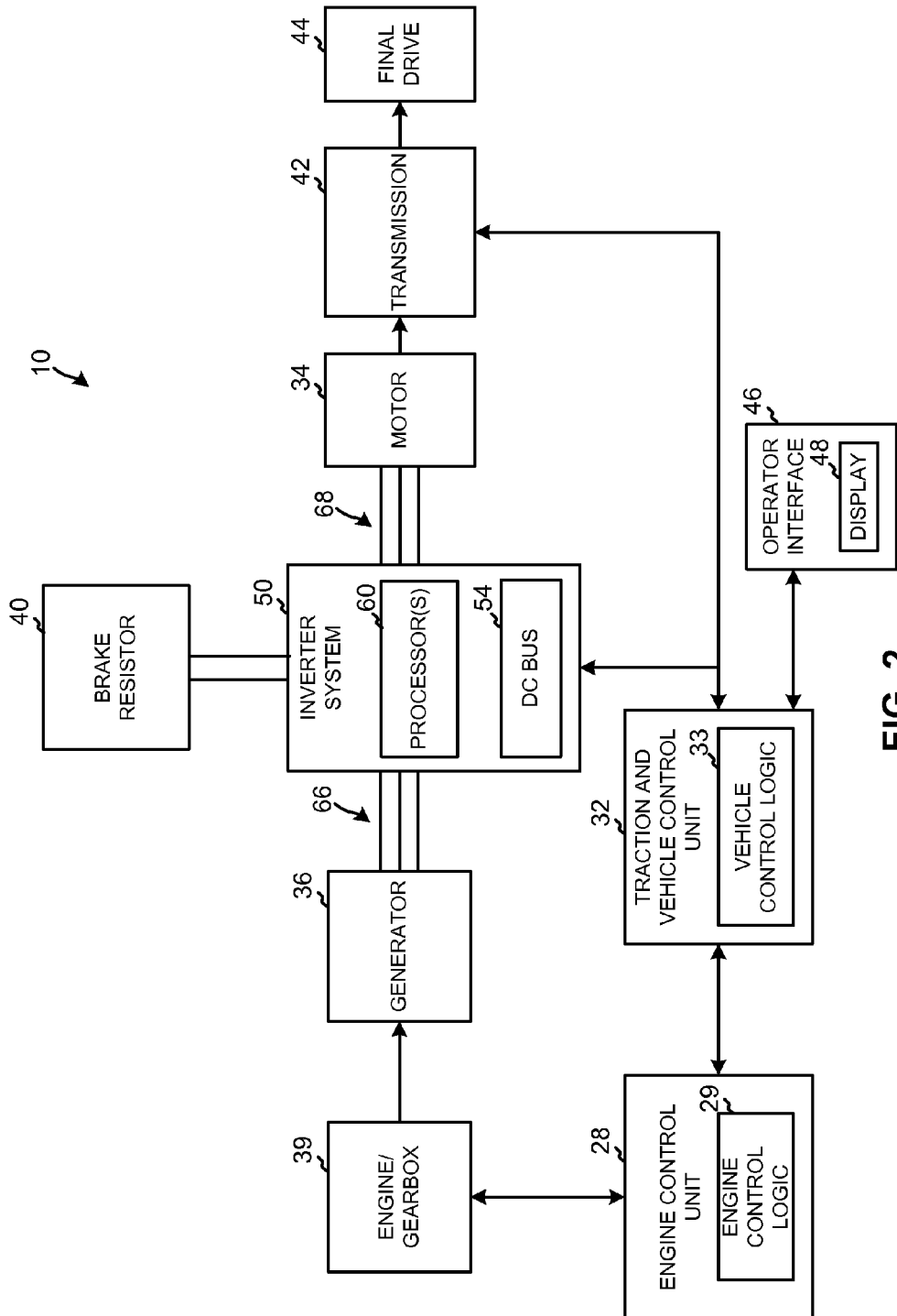
FAULT DETECTION SYSTEM AND METHOD FOR A GENERATOR

FIELD

The present disclosure relates to controlling an engine-driven generator of a vehicle, and more particularly to a system and method for detecting a phase-to-phase fault in an engine-driven generator of a vehicle.

BACKGROUND AND SUMMARY

Electric vehicles, such as hybrid vehicles or range extender vehicles, include one or more electric motors configured to drive a ground engaging mechanism of the vehicle. Electric vehicles typically include a generator driven by a prime mover, such as an engine, for generating electrical power used to drive the motor of the vehicle.

In some systems, electrical power from the generator is rectified and stored on a direct current (DC) bus for powering one or more loads on the vehicle, such as the electric motor. In some electric vehicles, the engine output is coupled to the generator such that the generator rotates as the engine rotates, including when the engine is idling. In these vehicles, the engine is shut down to stop rotation and power generation of the generator. The engine is often used to power other vehicle components, such as a hydraulic steering system and other vehicle hydraulics, for example. As such, keeping the engine running when the vehicle is stopped facilitates operation of the hydraulics and the vehicle controllers powered by the generator.

Generator system components occasionally fail for various reasons. One type of failure is a phase-to-phase fault, which may include the presence of a short circuit between phases of the generator output. Continued generation of power by the generator when there is a phase-to-phase fault may create a safety hazard, such as, for example, overheating of the generator components and the DC bus.

According to an embodiment of the present disclosure, an electric vehicle is provided that includes a chassis, a ground engaging mechanism configured to support the chassis, an engine, and a generator driven by the engine. The generator is configured to generate electrical energy and to provide the electrical energy on a multi-phase output. The vehicle further includes a DC bus configured to receive electrical energy provided from the generator and a sensor configured to detect an energy level on the DC bus. The vehicle further includes a controller configured to control routing of electrical energy from the multi-phase output to the DC bus. The controller is configured to monitor the energy level on the DC bus based on the sensor. The controller includes fault management logic operative to determine the presence of a fault between phases of the multi-phase output based on a comparison of the energy level on the DC bus to a threshold energy level.

According to another embodiment of the present disclosure, a fault detection method is provided for a vehicle having an engine-driven generator. The method includes providing a vehicle having a chassis, an engine, a generator driven by the engine, and a DC bus. The generator is configured to provide electrical energy on a multi-phase output. The method includes routing electrical energy from the multi-phase output to the DC bus and monitoring an energy level of the DC bus. The method further includes determining the presence of a fault between phases of the multi-phase output based on the energy level of the DC bus. In one example, the monitoring of the energy level includes monitoring the voltage level on the

DC bus, and the determining is based on a comparison of the voltage level on the DC bus to a threshold voltage level.

BRIEF DESCRIPTION OF THE DRAWINGS

The above-mentioned and other features and advantages of the invention, and the manner of attaining them, will become more apparent and the disclosure itself will be better understood by reference to the following description taken in conjunction with the accompanying drawings, wherein:

FIG. 1 illustrates an exemplary vehicle incorporating the fault detection system of the present disclosure;

FIG. 2 illustrates a representative view of an exemplary electric drive system of the vehicle of FIG. 1;

FIG. 3 illustrates a representative view of an exemplary power generation system of the vehicle of FIG. 1 including a generator, a controller, and a DC bus; and

FIG. 4 illustrates a flow chart of an exemplary method of detecting a phase-to-phase fault of the power generation system of FIG. 3.

Corresponding reference characters indicate corresponding parts throughout the several views. The exemplifications set out herein illustrate exemplary embodiments of the invention, and such exemplifications are not to be construed as limiting the scope of the invention in any manner.

DETAILED DESCRIPTION

The embodiments disclosed herein are not intended to be exhaustive or to limit the disclosure to the precise forms disclosed in the following detailed description. Rather, the embodiments are chosen and described so that others skilled in the art may utilize their teachings.

The term "logic" or "control logic" as used herein includes software and/or firmware executing on one or more programmable processors, application-specific integrated circuits (ASICs), field-programmable gate arrays (FPGAs), digital signal processors (DSPs), hardwired logic, or combinations thereof. Therefore, in accordance with the embodiments, various logic may be implemented in any appropriate fashion and would remain in accordance with the embodiments herein disclosed.

Referring to FIG. 1, an exemplary utility vehicle in the form of a loader 10 is illustrated. Although the utility vehicle is illustrated and described herein as loader 10, the utility vehicle 10 may include a motor grader, a tractor, a bulldozer, a feller buncher, a crawler, an excavator, a skidder, a forwarder, or another utility vehicle. Further, power generation system and fault management logic of the present disclosure may be used with a non-utility vehicle, such as any vehicle including a generator and a DC bus. Loader 10 includes a chassis 12 and a ground engaging mechanism 14. Ground engaging mechanism 14 is capable of supporting chassis 12 and propelling chassis 12 across the ground 15. Although the illustrated loader 10 includes wheels as ground engaging mechanism 14, loader 10 may include other ground engaging mechanisms, such as steel tracks, rubber tracks, or other suitable ground engaging members.

Loader 10 further includes a loader assembly 16. As illustrated in FIG. 1, loader assembly 16 includes a loader boom 18 and a work tool 20 in the form of a bucket. Work tool 20, which may be hydraulically controlled, may be capable of moving, excavating, plowing, or performing other material handling functions on a load 26, such as dirt or other materials. Other suitable work tools include, for example, blades, pallet forks, bail lifts, augers, harvesters, tillers, mowers, and grapples. Loader boom 18 is configured to move relative to

chassis **12** to move and operate work tool **20**. An operator controls the functions of loader **10**, including ground engaging mechanism **14** and loader assembly **16**, from an operator station **22** supported by chassis **12**.

Referring to FIG. **2**, vehicle **10** includes an electric drive system having a controller **50** configured to control one or more electric machines. Controller **50** may include one or more control units for controlling the one or more electric machines. Controller **50** includes at least one processor **60** having internal or external memory accessible by the at least one processor **60**. The at least one processor **60** executes instructions contained in software and/or firmware stored in the memory to perform the functionality of controller **50** described herein. In the illustrated embodiment, controller **50** is an inverter system **50** configured to control power generation from a generator **36** and to drive and/or control the loads connected to generator system output (e.g., DC bus **54**). Exemplary loads controlled by inverter system **50** include a motor **34** and a brake resistor **40**, although other suitable loads may be controlled. Additional or fewer electric machines may be controlled by inverter system **50**. In the exemplary embodiment, inverter system **50** includes a dual inverter motor drive configured to drive motor **34** with the power provided with generator **36**.

Motor **34** is configured to drive a transmission **42** and a final drive **44** (e.g., drive axle(s) coupled to ground engaging mechanisms **14**) of vehicle **10**. Additional motors **34** may be provided to drive one or more drive axles or ground engaging mechanisms **14** of vehicle **10**. In one embodiment, vehicle **10** may not include a transmission **42**, and the output of motor **34** may be coupled to final drive **44** for driving ground engaging mechanism **14**. In one embodiment, motor **34** includes a permanent magnet direct current (PMDC) machine, switched reluctance machine, or other suitable electric machine. In one embodiment, generator **36** includes a permanent magnet machine.

Generator **36** is coupled to a prime mover, illustratively an engine and gearbox assembly **39**, and is configured to generate electrical power for use by vehicle **10**. In particular, the rotation of engine **39** causes corresponding rotation of a rotor of generator **36**, thereby generating electrical power through windings of generator **36**. In one embodiment, engine **39** is a diesel engine, although other suitable engines may be used. Vehicle **10** includes an engine control unit (ECU) **28** in communication with a traction and vehicle control unit **32** for controlling engine **39**. In particular, ECU **28** includes engine control logic **29** operative to control the speed and operation of engine **39** based on control signals provided with control unit **32**. In one embodiment, an engine speed sensor is coupled to engine **39** for detecting the engine output speed and providing the detected engine speed to control unit **32** and/or to ECU **28**. In one embodiment, speed sensor **65** of FIG. **3** is used to detect the engine speed.

Multi-phase electric power is generated by generator **36** and provided on a multi-phase output that routes the electric power to inverter system **50**. In the illustrated embodiment, the multi-phase output includes multi-phase electrical lines **66**, such as electrical cables or other suitable conductors, as well as three-phase circuitry within generator **36** and inverter system **50**. In the illustrated embodiment, electrical lines **66** are three-phase electrical cables configured to route three-phase power from generator **36** to inverter system **50**. Inverter system **50** is operative to rectify the three-phase electrical power received on the multi-phase output and to provide the rectified power onto a direct current (DC) bus **54**, as described herein. Inverter system **50** is further operative to route power from DC bus **54** to one or more loads of vehicle **10**, such as to

motor **34**, a brake resistor(s) **40**, and/or other suitable loads. In an alternative embodiment, inverter system **50** may include another suitable energy storage device, such as a battery or fuel cell, for example, located internal or external to inverter system **50**. As described in greater detail herein with respect to FIG. **3**, inverter system **50** includes a processor **60** containing fault management logic **62** operative to detect and analyze faults with generator **36** and inverter system **50**.

Traction and vehicle control unit **32** of vehicle **10** is in communication with inverter system **50** and ECU **28**. Control unit **32** is operative to control the state of vehicle **10**, control and communicate with devices of an operator interface **46**, and issue commands to ECU **28** for controlling engine **39** and to inverter system **50** for controlling motor **34** and generator **36**. Control unit **32**, which includes a processor and software/firmware stored in memory accessible by the processor, includes vehicle control logic **33** operative to receive user input and monitored vehicle parameters for controlling various components and functionalities of vehicle **10** (e.g., transmission **42**, traction control, engine control, etc.) and to communicate control and feedback signals with inverter system **50**. A traction control unit and/or transmission control unit may alternatively be separate from and in communication with vehicle control unit **32**. Other suitable configurations of control unit **32** may be provided.

Control unit **32** is further operative to issue electric machine commands to inverter system **50**, and inverter system **50** controls motor **34** and generator **36** based on the received commands. In one embodiment, inverter system **50** provides vehicle parameters, such as motor and generator speed feedback, to control unit **32**. In one embodiment, transmission **42** may include a speed sensor providing transmission speed feedback to control unit **32**. In one embodiment, control unit **32** uses closed-loop controls for providing electric machine commands to inverter system **50** based on the received vehicle parameters (e.g., motor speed, generator speed, transmission speed, etc.).

In the illustrated embodiment, vehicle **10** further includes an operator interface **46** providing an operator with inputs, feedback, and controls for vehicle **10**. For example, operator interface **46** is provided in operator station **22** (see FIG. **1**) and may include a steering device, a brake, an accelerator, a transmission shifter, and other operator input devices. In the illustrated embodiment, one or more devices of operator interface **46** are in communication with control unit **32**. In one embodiment, control unit **32** may receive operator inputs from operator interface **46** and provide controls and commands to the appropriate controller **28**, **50** based on the received operator inputs. Operator interface **46** illustratively includes a display **48** that displays various vehicle parameters such as vehicle speed, ground speed, transmission gear data, temperature data, fault data, and other parameters provided with control unit **32**. In one embodiment, display **48** also provides diagnostic information received from inverter system **50**, ECU **28**, and/or control unit **32**. In one embodiment, control unit **32** issues motor and generator control commands to inverter system **50** and issues engine speed commands to ECU **28** over controller area network (CAN) communication. Other suitable communication protocols may be provided.

Referring to FIG. **3**, engine **39**, generator **36**, and inverter system **50** provide a power generation system **80** for vehicle **10**. In the illustrated embodiment, inverter system **50** includes power electronics **52** controlled by processor **60** to route three-phase electrical energy from generator **36** to DC bus **54**. In one embodiment, a capacitor bank **56** is coupled to DC bus **54** to establish potential on DC bus **54**. Capacitor bank **56**, which includes one or more capacitors, further serves as an

5

6

energy buffer to stabilize DC bus **54** at a predetermined voltage level. Processor **60** may control DC bus **54** to any suitable DC voltage level based on power electronics **52** and the activation and deactivation of loads. Power electronics **52** serve as a power converter (e.g., rectifier) for converting the AC power provided with generator **36** to DC power placed on DC bus **54**. Inverter system **50** further includes power electronics **70** controlled by processor **60** to direct the power on DC bus **54** to motor **34** and/or to other loads based on controls from processor **60**. In the illustrative embodiment, power electronics **52** receive AC power from generator **36** over three-phase power lines **66** and direct rectified DC power to capacitors **56**. Power lines **66** illustratively include a first phase line A, a second phase line B, and a third phase line C. Similarly, power electronics **70** are operative to invert DC power on DC bus **54** and route the inverted power to motor **34** over three-phase power lines **68**, such as electrical cables or other suitable conductors. Power lines **68** illustratively include a first phase line X, a second phase line Y, and a third phase line Z. Other suitable drivers may be used to route power to and from electric machines **34**, **36**.

Inverter system **50** further includes a braking chopper **41** or other suitable switch device that is controlled by processor **60** to selectively route power from DC bus **54** and/or motor **34** to brake resistor(s) **40**. In one embodiment, braking chopper **41** is controlled to draw current or bleed energy from DC bus **54** to brake resistor **74**, as described herein. Braking chopper **41** may be separate from or integrated with power electronics **70**. In one embodiment, inverter system **50** routes excess energy generated from motor **34** to brake resistor **40** upon motor **34** reducing speed. Brake resistor **40** absorbs and dissipates received energy into heat.

In one embodiment, control unit **32** of FIG. **2** provides controls and other parameters to inverter system **50** for controlling power electronics **52**, **70**. In the illustrated embodiment, a voltage sensor **64** is coupled to capacitor bank **56** and/or DC bus **54** for providing a signal representative of measured voltage on DC bus **54** to processor **60**. In one embodiment, power electronics **52**, **70** include a plurality of power semiconductors, such as insulated-gate bipolar transistors (IGBT's) or MOSFET devices, for example, controlled by processor **60** and configured to control the flow of current provided with generator **36** to DC bus **54** and from DC bus **54** to motor **34** and brake resistor **40**.

In one embodiment, each phase of power lines **66**, **68** includes a current sensor **58** for measuring the current through the respective phases of power lines **66**, **68**. In particular, a current sensor **58a** is coupled to first phase line A, a current sensor **58b** is coupled to second phase line B, and a current sensor **58c** is coupled to third phase line C. Similarly, a current sensor **58x** is coupled to first phase line X, a current sensor **58y** is coupled to second phase line Y, and a current sensor **58z** is coupled to third phase line Z. In one embodiment, current sensors **58** provide feedback signals to processor **60** indicative of the measured current through the respective power line **66**, **68**. An exemplary current sensor **58** is an open loop Hall effect current transducer.

Fault management logic **62** of inverter system **50** of FIG. **3** is operative to detect and analyze faults associated with inverter system **50**, generator **36**, and motor **34**. In the illustrated embodiment, fault management logic **62** is operative to detect a short circuit condition between phases of the three-phase output from generator **36** based on a monitored energy level of DC bus **54**. Fault management logic **62** is further operative to monitor for an overcurrent condition on the three-phase output from generator **36**.

Referring to FIG. **4**, a flow diagram **100** of an exemplary method performed by fault management logic **62** of inverter system **50** is illustrated for detecting and analyzing a fault associated with power generation system **80**. Reference is made to FIGS. **1-3** throughout the description of FIG. **4**. At block **102**, during operation of engine **39**, fault management logic **62** detects a fault with inverter system **50** and/or generator **36**. In one embodiment, the detected fault is an overcurrent condition from the output of generator **36**, although other suitable faults may be detected. In particular, fault management logic **62** monitors the current level on each power line **66** and determines an overcurrent condition upon the monitored current level exceeding a threshold current level stored in memory. Upon detection of the fault at block **102**, fault management logic **62** causes engine **39** to operate at an idle speed. For example, fault management logic **62** issues a command signal to control unit **32** instructing that an overcurrent condition or other fault has been detected, and control unit **32** instructs ECU **28** to operate engine **39** at the idle speed or at another suitable low engine speed. An exemplary engine idle speed is 900 revolutions per minute (RPM), although other suitable idle speeds may be implemented. As such, both engine **39** and generator **36** are run at idle speed upon detection of the fault. In addition, fault management logic **62** disables the control of generator **36** at block **106** upon detection of the fault.

In one embodiment, disabling the control of generator **36** at block **106** involves opening all generator power semiconductors (e.g., IGBTs). In one embodiment, the motor load is disabled from inverter system **50** at block **106**. In another embodiment, the motor load is not disabled and the motor **34** is run at reduced power with an uncontrolled DC bus **54**. In one embodiment, upon detecting an asymmetric fault at block **102** wherein an IGBT/diode pair is shorted, one set of IGBTs is turned off and another set of IGBTs is turned on (depending on which IGBT is detected as shorted) to limit the fault current.

Fault management logic **62** monitors an energy level, illustratively the voltage (i.e., potential energy) level, on DC bus **54** with voltage sensor **64**. Upon engine **39** being operated at low idle speed, fault management logic **62** bleeds down the voltage on DC bus **54**, as represented at block **108**. In the illustrated embodiment, fault management logic **62** bleeds down the DC bus voltage by activating braking chopper **41**, thereby allowing the energy on DC bus **54** to dissipate to brake resistor **40**. The DC bus voltage may be bled down using another suitable method or device. In one embodiment, braking chopper **41** is switched on at block **108** for a predetermined duration, such as one minute for example or another suitable duration, to allow the DC bus voltage to stabilize or reduce to a desired level. Alternatively, fault management logic **62** monitors the voltage level on DC bus **54** at block **108** after activating braking chopper **41**, and fault management logic **62** deactivates braking chopper **41** once the monitored DC bus voltage has stabilized and/or returned to below a voltage level threshold.

At block **110**, after the predetermined duration has passed and/or braking chopper **41** has been switched off, fault management logic **62** determines whether the generator loads are all disabled, including motor **34** and braking chopper **41**, for example. In particular, fault management logic **62** verifies that the current to brake resistor **40** is close to or about zero amps (A) and that the motor control is disabled. If the loads are not disabled, the method returns to block **106** to disable the generator controls. If the loads are disabled at block **110**, fault management logic **62** continues to monitor the voltage level on DC bus **54** with voltage sensor **64** and the speed of

generator **36** with a speed sensor **65** (FIG. **3**). Speed sensor **65** may include any suitable sensor operative to detect the rotational speed of generator **36** or engine **39**. Based on the speed of generator **36**, fault management logic **62** calculates an expected voltage level on DC bus **54** with all loads (e.g., motor **34**, brake resistor **40**, etc.) disabled. In one embodiment, the expected voltage level on DC bus **54** is calculated further based on an expected or estimated temperature of the generator permanent magnets and on the known geometry of generator **36**. In one embodiment, the temperature is estimated or calculated using an electromagnet observer. In one example, an expected voltage level on DC bus **54** for a generator idle speed of 900 RPM at a particular generator magnet temperature is about 150 VDC. Other suitable expected voltage levels may be calculated based on the system configuration and generator speed and temperature. In one embodiment, fault management logic **62** adjusts the expected voltage level based on a detected change in the generator speed.

Based on the expected DC bus voltage level, fault management logic **62** determines a threshold voltage level for use in the comparison block **114** of FIG. **4**. For example, the threshold voltage level of block **114** may be calculated by adding a voltage offset to the expected DC bus voltage level. In one example, a voltage threshold of 220 V is selected based on a calculated expected DC bus voltage of 150 V, although other suitable voltage thresholds may be selected based on system configuration.

In one embodiment, fault management logic **62** calculates the expected DC bus voltage and the voltage threshold at block **112** based on formulas stored in memory of processor **60**. In other embodiments, a lookup table is stored in memory of inverter system **50** containing expected DC bus voltages that correspond to combinations of generator speed, magnet temperature, and generator geometry. Similarly, the lookup table may contain DC bus voltage thresholds that correspond to the expected DC bus voltages. As such, fault management logic **62** may look up and retrieve the DC bus voltage threshold and/or the expected DC bus voltage level in block **112**. In other embodiments, the DC bus voltage threshold of block **114** is predetermined and stored in memory of inverter system **50**.

At block **114**, with the voltage threshold calculated, fault management logic **62** compares the monitored DC bus voltage (determined with voltage sensor **64**) and the calculated voltage threshold. If the monitored DC bus voltage does not exceed the voltage threshold at block **114**, fault management logic **62** decrements a fault counter at block **116** (or holds the fault counter at zero) and returns to block **110** to continue monitoring the DC bus voltage. If the monitored DC bus voltage exceeds the voltage threshold at block **114**, fault management logic **62** increments the fault counter at block **118** and compares the fault counter to a counter threshold at block **120**. If the fault counter exceeds the counter threshold at block **120**, fault management logic **62** determines at block **124** that a phase-to-phase fault, i.e., a short circuit between phases of the three-phase generator output, exists in the system. Fault management logic **62** then issues a notification signal to control unit **32** to notify the control unit **32** that the phase-to-phase short circuit fault has been detected. In response to the fault notification signal, control unit **32** instructs ECU **28** to shut down engine **39**. In the illustrated embodiment, control unit **32** first provides a warning to the operator that engine **39** will be shut down, and control unit **32** shuts down engine **39** after a suitable delay following the warning to the operator. As such, rotation of generator **36** is stopped to reduce the likelihood of driving energy into the faulted area of the system.

In the illustrated embodiment, the fault counter threshold of block **120** is programmed to provide a suitable delay after first detecting that the DC bus voltage exceeds the calculated voltage threshold at block **114**. For example, a threshold counter of five requires that fault management logic **62** detect the DC bus voltage exceeding the voltage threshold for at least five iterations of the control loop. As such, the likelihood of a false analysis by fault management logic **62** is reduced. For example, fault management logic **62** is less likely to determine a fault exists due to a momentarily high or false voltage reading on DC bus **54**.

While the voltage level on DC bus **54** is monitored and compared to a threshold in the illustrative embodiment, other suitable measures of energy on the DC bus **54** may be used to implement the method described herein. In one embodiment, the current level or other energy level may be monitored and compared with a threshold.

In one embodiment, control unit **32** issues a fault warning signal (e.g., audible or visual) to operator interface **46** to notify the operator of the phase-to-phase short circuit fault. The warning signal may warn the operator that engine **39** will be shut down. Alternatively, the warning signal may recommend that the operator manually shut down engine **39**. In one embodiment, control unit **32** requires that the operator manually initiate the shutdown of engine **39** after issuance of the fault warning signal. In one embodiment, control unit **32** automatically initiates the shutdown of engine **39** following a predetermined delay after receiving the fault notification signal from fault management logic **62**. An exemplary shutdown delay is one to five minutes, although any suitable delay may be implemented.

In one embodiment, fault management logic **62** exits the fault analysis method of FIG. **4** and returns to normal operation upon the generator controls being enabled (e.g., upon motor **34** being enabled) or upon the engine speed deviating a specified amount from the engine idle speed. For example, fault management logic **62** may exit the fault analysis method of FIG. **4** upon the engine speed deviating from the engine idle speed by ±10% or another suitable percentage. Upon exiting the fault analysis mode, the fault counter of blocks **116**, **118** is cleared back to zero.

In the illustrated embodiment described with respect to FIG. **4**, fault management logic **62** enters a fault analysis mode upon detecting a fault condition, such as an overcurrent condition or other fault, at block **102** to determine the cause of the fault condition. In an exemplary embodiment described herein, fault management logic **62** determines if a short circuit exists between phases of the three-phase generator output upon detection of an overcurrent fault. In particular, fault management logic **62** detects a phase-to-phase short circuit based on an elevated DC bus voltage. The elevated DC bus voltage may be due to, for example, flux strengthening of the generator magnets resulting from the fault current and voltage phase relationships. As such, fault management logic **62** is operative to initiate the shutdown of engine **39** upon a determination that the overcurrent fault is due to a phase-to-phase short circuit. However, other suitable causes of the overcurrent fault may be monitored and analyzed by fault management logic **62**. For example, fault management logic **62** may detect failed sensors (e.g., current sensors **58**, voltage sensor **64**, etc.), damaged cables **66**, **68**, a short circuit or other circuit interruption in other areas of inverter system **50**, or other suitable faults.

In one embodiment, fault management logic **62** monitors the DC bus voltage during other conditions of power generation system **80** in addition to the overcurrent condition or other fault condition. For example, fault management logic

62 may monitor for the phase-to-phase short circuit whenever engine **39** is idling and the generator loads are disabled or at other suitable operating conditions.

While fault management logic **62** is described herein as being provided in inverter system **50**, fault management logic **62** may alternatively be located in vehicle control unit **32** or shared between inverter system **50** and vehicle control unit **32**. Other suitable configurations of fault management logic **62** may be provided.

In another embodiment, fault management logic **62** detects a phase-to-phase fault of the three-phase generator output by monitoring for a ground fault. In this embodiment, the voltage system of vehicle **10** (e.g., provided with inverter system **50**) is floating, i.e., not grounded to the frame or chassis **12**. Fault management logic **62** monitors the resistance between the voltage system and chassis **12**. If the resistance is below a predetermined resistance threshold, fault management logic **62** determines a fault exists. An exemplary fault detected with this method is the output phases of the generator being shorted to ground. Fault management logic **62** may implement a delay after initially detecting the low resistance before determining the fault exists.

While this invention has been described as having preferred designs, the present invention can be further modified within the spirit and scope of this disclosure. This application is therefore intended to cover any variations, uses, or adaptations of the invention using its general principles. Further, this application is intended to cover such departures from the present disclosure as come within known or customary practice in the art to which this disclosure pertains and which fall within the limits of the appended claims.

The invention claimed is:

1. An electric vehicle including:
a chassis;
a ground engaging mechanism configured to support the chassis;
an engine;
a generator driven by the engine, the generator being configured to generate electrical energy and to provide the electrical energy on a multi-phase output;
a DC bus configured to receive electrical energy provided from the generator;
a sensor configured to detect an energy level on the DC bus; and
a controller configured to control routing of electrical energy from the multi-phase output to the DC bus and to monitor the energy level on the DC bus based on the sensor, the controller including fault management logic operative to
detect a fault condition, and
determine that the fault condition is a phase-to-phase fault affecting relative distribution of the electrical energy on the phases of the multi-phase output based on a comparison of the energy level on the DC bus after detecting the fault condition to a threshold energy level.

2. The vehicle of claim **1**, wherein the fault management logic is further operable to determine that the phase-to-phase fault includes a short circuit between phases of the multi-phase output.

3. The vehicle of claim **1**, wherein the sensor is configured to detect a voltage level representative of the energy level, and the fault management logic determines that the fault condition is a phase-to-phase fault based on a comparison of the voltage level on the DC bus to a threshold voltage level.

4. The vehicle of claim **3**, wherein the fault management logic determines that the fault condition is a phase-to-phase

fault when the voltage level on the DC bus exceeds the threshold voltage level for a predetermined duration.

5. The vehicle of claim **1**, wherein the fault management logic issues a command to shut down the engine upon determining that the fault condition is a phase-to-phase fault and determining that the energy level on the DC bus exceeds the threshold energy level.

6. The vehicle of claim **1**, further including a current sensor configured to detect a current level of the multi-phase output, the fault management logic being operative to detect the fault condition by detecting an overcurrent condition based on the current sensor prior to determining that the fault condition is a phase-to-phase fault.

7. The vehicle of claim **6**, wherein, upon detection of the overcurrent condition, the fault management logic is further operative to stabilize the DC bus voltage, and wherein the fault management logic is operative to determine that the fault condition is a phase-to-phase fault based on the comparison of the energy level on the DC bus following the stabilization of the DC bus voltage.

8. The vehicle of claim **1**, wherein the fault management logic is operative to calculate the threshold energy level as an expected energy level on the DC bus based on a speed of the generator.

9. The vehicle of claim **1**, further including an electric motor operative to drive the ground engaging mechanism, the controller selectively routing electrical energy from the DC bus to the electric motor to drive the motor, and wherein the fault management logic is operative to stabilize the DC bus voltage by controllably dissipating energy from the DC bus to an electric braking system of the ground engaging mechanism.

10. The vehicle of claim **1**, wherein the engine is fixedly coupled to the generator such that rotation of the engine output shaft causes corresponding rotation of the generator.

11. The vehicle of claim **1**, wherein the multi-phase output includes three-phase power conductors routed from the generator to the controller.

12. A fault detection method for a vehicle having a chassis, an engine, a generator driven by the engine, and a DC bus, the generator being configured to provide electrical energy on a multi-phase output, the method comprising:
routing electrical energy from the multi-phase output to the DC bus;
detecting a fault condition;
monitoring an energy level of the DC bus after detecting the fault condition; and
determining that the fault condition is a phase-to-phase fault affecting relative distribution of the electrical energy on the phases of the multi-phase output based on the energy level of the DC bus after detecting the fault condition.

13. A method for detecting and evaluating a fault condition in a vehicle, the vehicle including an engine, a generator driven by the engine, a power converter, a DC bus, and an electrical vehicle braking system, the generator being configured to provide electrical energy on a multi-phase output, and the power converter being configured to rectify the multi-phase output and provide a rectified power output to the DC bus, the method comprising:
detecting a current level on at least one phase of the multi-phase output;
comparing the detected current level to a threshold current to detect an overcurrent fault condition;
stabilizing the DC bus voltage in response to detecting the overcurrent fault condition by reducing a speed of the

generator driven by the engine and controllably dissipating energy from the DC bus to the electrical vehicle braking system;

determining a voltage threshold based on the speed of the generator after stabilizing the DC bus voltage; and

determining that the overcurrent fault condition is caused a short-circuit between phases of the multi-phase output based on a comparison of the stabilized DC bus voltage to the determined voltage threshold.

14. The fault detection method of claim **12**, further comprising stabilizing the energy level of the DC bus in response to detecting the fault condition, and wherein determining that the fault condition is a phase-to-phase fault includes determining that the fault condition is a phase-to-phase fault based on the energy level of the DC bus after stabilizing the energy level of the DC bus.

15. The method of claim **14**, wherein monitoring the energy level of the DC bus includes monitoring a voltage level on the DC bus using a voltage sensor after stabilizing the

energy level of the DC bus, and wherein determining that the fault condition is a phase-to-phase fault based on the energy level of the DC bus after stabilizing the energy level of the DC bus includes

determining a threshold voltage level indicative of an expected voltage level on the DC bus based on a speed of the generator after stabilizing the energy level of the DC bus, and

comparing the voltage level on the DC bus after stabilizing the energy level of the DC bus to the threshold voltage level.

16. The fault detection method of claim **14**, wherein stabilizing the energy level of the DC bus includes controllably dissipating energy from the DC bus to a braking system of the vehicle.

17. The fault detection method of claim **14**, wherein stabilizing the energy level of the DC bus includes slowing a speed of the generator.

* * * * *